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Spatial hydrological responses to land use and land cover changes in a typical catchment of the Yangtze River Delta region

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ABSTRACT

This study assessed the individual and combined effects of land-use and land-cover changes (LUCCs) on spatial hydrological responses by using an integrated approach involving the Soil and Water Assessment Tool (SWAT) and geographically weighted regression (GWR) models in the Xitiaoxi River Basin (XRB). The LUCCs and their spatial patterns from 1985 to 2008 were evaluated in the XRB. The hydrological processes during the period from 1980–2015 were then generated by the SWAT model under the 1985 and 2008 land-use scenarios. GWR models were constructed to quantify the spatial impacts of LUCCs at the sub-basin scale. The results showed that the predominant trend of land-use conversion was between forest-grass land and agricultural land, and the diminishing portion of forest-grass land (25.93 km^2) and agricultural land (46.77 km^2) contributed to the expansion of urban land during the period 1985–2008. Moreover, the urban area increased from 5.6% to 17.05%, and the change ratio progressed towards the centre of the XRB. These changes in land use caused the average annual water yield and surface runoff to increase by 1.09% and 11.87%, respectively, and the average annual evapotranspiration (ET), percolation and baseflow to decrease by 0.73%, 16.53% and 17.26%, respectively. In addition, the results of the GWR models indicated that the responses of each hydrological component exhibited spatial differences. The comprehensive land-use intensification index (*La*), selected to reflect the combined effects of LUCCs, was positively correlated with water yield and surface runoff but negatively correlated with ET, percolation and baseflow. *La* had a greater effect on water yield, surface runoff, percolation and baseflow in rural areas than in the urbanized region. The combined effects of LUCCs in certain local areas increased water yield and surface runoff by up to 13.7% and 114.2%, respectively. The local coefficient indicated that rural regions might be exposed to greater effects of LUCCs. The results of this study could be useful to understand the effects of LUCCs on the spatial patterns of each hydrological component and to help improve flood control and water resource management.

1. Introduction

Variation of hydrological components caused by climate changes and anthropogenic activities, such as land-use and land-cover changes (LUCCs), has resulted in numerous environmental problems (Mittal et al., 2016; Woldesenbet et al., 2016; Zhang et al., 2016; Rose and Peters, 2001; Wang et al., 2014). In particular, in the process of rapid urbanization, regional hydrological characteristics have changed significantly because a large portion of the permeable land surface has been replaced by impervious surfaces (Zhou et al., 2013). Quantitative assessment of LUCCs and their hydrological impacts has been one of the hotspots of current hydrological researches, which could facilitate the development of sustainable water resource strategies and the improvement of land management options (Ghaffari et al., 2010; Tekleab et al., 2014).

Many studies have investigated the effects of LUCCs on hydrological processes in different geographical regions (Ye et al., 2009; Chen et al., 2014; Zuo et al., 2016; Ghaffari et al., 2010; Nadal-Romero et al., 2016; Woldesenbet et al., 2016; Zhang and Schilling, 2006). These studies examined the hydrological response of an entire basin, which was based mainly on a hydrological model only (Sajikumar and Remya, 2015; Fossey et al., 2016) or a hydrological model and traditional statistical methods (Nie et al., 2011; Shi et al., 2014; Woldesenbet et al., 2016; Yan et al., 2013; Zhang et al., 2012; Yan et al., 2018; Wagner and Waske, 2016). These results reflected the average effects of LUCCs on the hydrological processes of the entire basin. However, the relationship between LUCCs and hydrological components could not be quantitatively evaluated exclusively based on hydrological models (Yan

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et al., 2018; Zuo et al., 2016). In addition, the traditional statistical methods, such as linear and multiple linear regression models, logistic regression models, partial least squares regression models and principal components analysis, assume the relationships between variables are constant over the entire drainage area. Therefore, these results show the average of existing relationships, which may neglect some significant spatial characteristics and may hide local variations (Chen et al., 2016; Tu and Xia, 2008).

Some recent studies showed that the hydrological impacts of LUCCs in different regions differed due to the spatial heterogeneity of physical geographical components, such as land use, topography, and soil, and so on (Chang et al., 2014; Zhou et al., 2013; Wang et al., 2017). For instance, Beighley et al. (2003) and Brun and Band (2000) found that urbanization increased peak discharges and runoff volume but decreased streamflow variability and baseflow, whereas David et al. (2005), Jennings and Jarnagin (2002) and Kim et al. (2002) suggested that an increase in the impervious area led to contrasting effects on baseflow and streamflow. Additionally, Shi et al. (2014) found that an increase in grassland had a positive relationship with surface runoff in the upstream region of the Luanhe River Basin but a negative relationship in the downstream region. Similarly, Yan et al. (2018) and Zuo et al. (2016) also found that the responses of hydrological components to LUCCs exhibited spatial differences at the sub-basin scale in the Loess Plateau of China. Hence, the hydrological effects of LUCCs may differ between local and global scales.

Recently, a spatial analysis method called geographically weighted regression (GWR) has increasingly been used to detect the causes of spatial variation in geographical entities, such as river discharge (Rennermalm et al., 2012), mean annual precipitation (Yue et al., 2013), annual runoff (Chang et al., 2014), and surface water quality (Chen et al., 2016; Tu and Xia, 2008). The model can effectively solve the spatial non-stationarity issue by allowing regression model parameters to change over space. In addition, GWR considers the spatial autocorrelation of variables, which is difficult to address in traditional statistical models such as ordinary least squares (OLS) regression (Chen et al., 2016; Fotheringham et al., 1996). Nevertheless, only a few studies have investigated spatial hydrological responses to individual and combined effects of LUCCs by combining a distributed hydrological model and spatial analysis model.

Therefore, the objectives of this research are to identify the most suitable statistical model to describe the spatial relationship between hydrological fluxes and land-use variables and to explore the spatial patterns of hydrological responses to individual and combined effects of LUCCs. To achieve these objectives, LUCCs and their spatial patterns from 1985 to 2008 were evaluated in the study area. Then, the water balance changes of the basin were estimated based on the calibrated SWAT model, and finally, the spatial hydrological responses to the individual and combined effects of LUCCs were assessed through GWR models, which were compared with OLS models.

2. Materials and methods

2.1. Study area

The study area is in the Xitiaoxi river watershed (1371 km^2), where located in the northwestern region of the Yangtze River Delta between longitudes 119°14′E–119°45′E and latitudes 30°23′N–31°11′N (Fig. 1). Xitiaoxi River, one of the main tributaries in the upstream region of Taihu Lake, comprises five main branches: the Dipu stream, the Hu stream, the Dragon stream, the South stream and the West stream. The area is characterized by mountains, and its elevation ranges between 5 and 1580 m above sea level. With a humid subtropical monsoon climate, the average annual precipitation and temperature were 1584.01 mm and 15.5 °C, respectively, during the study period from 1978 to 2015.

There are two large flood-proofing reservoirs (i.e., Fushi and Laoshikan reservoirs) in the headwaters of Xitiaoxi River, and the main land-use type in the upstream region of these reservoirs is forest that has experienced little change. In this paper, the Xitiaoxi River Basin (XRB, 661.28 km^2), which extends between the two reservoirs and the basin outlet (i.e. Hengtangcun station), had undergone large urbanization and was selected as the study area. The actual outputs of the two reservoirs (i.e., actual daily streamflow) were input as the upstream boundary conditions of the hydrological model.

Allowing for the XRB's elevation and ongoing urban expansion, we divided the XRB into eight zones: the urban area (UA, 69.46 km^2), three suburban areas, i.e., SADX (53.67 km^2), SAMX (79.21 km2) and SAMHD (64.65 km^2), and four mountainous areas, i.e., LMUD (63.38 km^2), LMUW (80.08 km^2), LMUS (60.6 km^2) and HMUHD (190.77 km^2) (Table 1).

2.2. Datasets

The datasets of this study mainly included spatial data, such as topography, soils and land use, and hydrometeorological data. Topography was presented by a digital elevation model that was derived from 1:10,000 topographic contour data. Soil spatial data with a scale of 1:10,000 were obtained from the National Second Soil General Survey data, and soil property information was provided by the Anji Bureau of Agriculture. The land-use maps for 1985 were obtained by digitizing land survey data (1:10,000) that had high accuracy and reliability. Landsat TM images were selected as the data source to extract land-use data for 2008 using methods of supervised classification and manual interpretation, and the results showed an acceptable precision (Zhou et al., 2013). Therefore, the accuracy of these spatial data met the requirement for the research. In addition, the above spatial data had raster-based formats and all are unified into 30 m × 30 m resolution.

The hydrometeorological data from 1977 to 2015 at a daily interval included streamflow from three stations for two reservoirs and the outlet of the basin, precipitation from 16 rain gauge stations and weather data from a meteorological station (Fig. 1). Weather data consisted of daily precipitation, maximum and minimum temperature, relative humidity, mean wind speed and daily solar radiation. These data were supplied by the local Hydrology and Water Resources Investigation Bureau and were corrected before publication with a very small percentage of missing data. The few missing data points were filled using calculated data based on neighbouring stations through a simple linear regression method.

2.3. Methodology

In this study, the spatial response patterns of hydrological components to LUCCs in the XRB were detected through the coupling of hydrological modelling and a spatial regression model. First, the spatial patterns of response and explanatory variables from 1985 to 2008 were evaluated in the XRB; then, the water balance changes in the basin were estimated based on the calibrated SWAT model; and finally, the spatial hydrological responses to the individual and combined effects of LUCCs were assessed through spatial regression models.

2.3.1. Land-use variables and hydrological variables

To analyze the effects of LUCCs on regional hydrological process, this study selected hydrological components (i.e. water yield, surface runoff, actual evapotranspiration (ET), percolation and baseflow) as response variables. The explanatory variables include four land-use variables (i.e. forest-grass land, agricultural land, urban land and water bodies) and a comprehensive index of land-use intensification degree (*La*).

La is used as an indicator of urbanization and land-use intensity (Zhuang and Liu, 1997). This index can reflect the impact of human factors on the land system and can quantitatively measure the level of intensive land use (Gao et al., 2015). *La* is calculated as follows (Hu